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NOTES AND CORRESPONDENCE

Model Simulation of Impacts of Transient Surface Wetness on Summer Rainfall in the United States Midwest during Drought and Flood Years

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ABSTRACT

Surface moisture availability has been hypothesized by various investigators to provide additional negative (positive) feedback on rainfall during summer drought (flood) conditions in the Midwest. In this note, we report on a preliminary numerical modeling effort in which the impact of transient changes in surface wetness on summer rainfall events in the midwestern United States during two recent drought and flood years is assessed. It was found that during the drought of 1988, hypothetical temporary extreme moistening of the surface resulted in large relative increases in simulated rainfall, often by as much as a factor of 2. However, from an agricultural perspective these large relative changes in rainfall might not necessarily have translated into meaningful increases since the original absolute rainfall amounts were quite small. In the flood year of 1993, an assumed transient drying of the surface resulted in relative decreases in simulated rainfall by as much as 30%–40%. This relative decrease in rainfall did, however, translate into a discernible drop in the absolute rainfall.

1. Introduction

In recent years extreme warm-season events (drought in 1988 and widespread flooding in 1993) have had severe economic and societal impact on the central United States. To illustrate the severity of these events consider that in 1988 the statewide average June and July rainfall in Iowa was only 46% of its normal value of 219 mm and that July had been the wettest month up to that point in the year (H. Hillaker 1994, personal communication). Iowa, which was typical of many states in this region, suffered one of its worst droughts on record that year. By contrast, in 1993 this region experienced record flooding associated with one of the wettest summers on record. For example, Iowa, which was again typical for the region, had a statewide average rainfall of 476 mm in June and July, this was 217% of normal (H. Hillaker 1994, personal communication). Both of these extreme events resulted in heavy financial losses for the agricultural community, and the flooding caused additional hardship and personal loss in many urban communities.

It has been hypothesized that disturbances in the global atmospheric circulation caused by El Niño–related sea surface temperature anomalies are linked to such extreme weather events (Trenberth et al. 1988; Mo et al. 1991). Another mechanism, although controversial, that has been suggested as being partially responsible for the recent events is global warming due to increased atmospheric levels of CO_2 (Kerr 1989). Seasonal anomalies in surface moisture have also been thought to contribute to the severity and extent of such events (e.g., Namias 1959; Meehl and Washington 1988). A GCM study by Atlas et al. (1993) suggested that dry surface conditions contributed to the severity of the 1988 drought via a negative feedback on rainfall. Summer GCM simulations forced with both wet and dry anomalies of surface moisture availability in Europe indicated corresponding anomalies of increased and decreased rainfall (Rowntree and Bolton 1983). GCM studies reported in Mintz (1984) have shown, in general, increased rainfall resulting from continental increases in surface moisture availability.

In contrast to GCM studies examining soil moisture effects on *continental-scale* precipitation, no attempt has been made to examine the hypotheses relating surface-moisture anomalies to the extremes of drought and flood on a *regional scale.* However, some relevant bulk estimations have been carried out. For example, Mintz (1984) estimates that surface evapotranspiration is an important determinant of July precipitation in the central and eastern United States. On the other hand, Fritsch et al. (1986) concluded that even in large-scale drought regimes mesoscale convective systems (MCSs) occurred as often as in normal years, but they

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tend to be smaller and less efficient in producing precipitation. This is further suggestive of some surface moisture feedback since about one-half of this region's rainfall is produced by MCSs (Heidman and Fritsch 1984).

Modeling of regional convective rainfall events requires refinements in grid resolution and the representation of additional physical processes that are unavailable in GCMs. A regional atmospheric model, with these refinements, has been used in this study to provide *preliminary* evaluations of the impact of transient regional anomalies of surface wetness on specific rainfall episodes during the Great Plains drought of 1988 and the flood of 1993. A sample of representative rainy days in 1988 and 1993 was simulated where the regional atmospheric model was forced with the observed extreme surface-wetness conditions and then with contrasting (hypothetical) conditions of the opposite extreme. The contrasting conditions are assumed to persist only for the duration of the simulations. Differences in rainfall between the simulations are used to infer the impact of surface wetness on rainfall during these events.

2. Methodology

The Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM4) (Anthes et al. 1987) was adopted for the simulations. This hydrostatic model has been used widely in various geographical locations to simulate various meteorological phenomena such as heavy rainfall events, explosive cyclogenesis, and transport of air pollutants (Anthes 1990). This research-oriented model offers different options for major model physical processes pertaining to cumulus convection, cloud physics, and boundary layer processes. Table 1 lists the model configuration and key parameters used in this study.

The raw meteorological data used in this study are the conventional upper-air soundings (mandatory levels only) and surface observations. The data, available at 12-h intervals, were first interpolated horizontally onto model grid points and then vertically to the model sigma levels. Surface evaporation is computed using the surface moisture availability m approach ("β scheme"). This simplification is justified given the level of uncertainties in determination of the surface wetness. Note $m = 1$ implies that the actual surface evaporation will equal the potential evaporation, and $m = 0$ implies that there is no moisture available for surface evaporation. Because no directly observed surface wetness values were available, crop moisture and Palmer drought indices were used to infer surface wetness.

Three representative rainy days from July of 1988 and four from July 1993 were selected for the 24-h simulations. All the simulations commenced at 1200 UTC (0600 CST) with initial fields derived from radiosonde data. The selected days are ones for which rainfall was reported over the interior of the simulation domain. Because of the observed nocturnal maximum in precipitation over this region, selected days included cases where nocturnal precipitation occurred. Table 1 summarizes the simulations that were carried out for this study. For summer 1988, the first set of simulations used observed surface conditions (unmodified simulations) m_{ob}, the second set used saturated surface conditions m_s over the entire simulation domain, and the third set had saturated surface moisture conditions prescribed over only a specific subdomain with observed conditions in the rest of the domain. Likewise, a similar series of simulations was carried out for summer 1993, except that to contrast the observed very wet conditions over the central part of the domain, dry surface conditions m_d were prescribed over the entire domain for the second set of simulations and over the subdomain for the third set of simulations. The subdomain for the 1988 cases was that area most affected by drought, hereafter referred to as the "drought-stricken region." Likewise for 1993, the subdomain selected was that region most affected by flooding, hereafter referred to as the "flood-stricken region."

TABLE 1. Model input parameters and simulation characteristics.

Horizontal grid spacing: 60 km
Convective scheme: Kuo–Anthes
High resolution PBL
Hydrostatic
Simulation domain centered at 38°N, 96°W (51 × 41 grid)
Surface moisture availability m
case (i): observed m, inferred from maps of Palmer and crop moisture indices; m_{ob}
case (ii): saturated, $m = 0.99$; m_s
case (iii): dry, $m = 0.01$; m_d
Commencement: 1200 UTC
Duration: 24 h
Simulated days
1988: 7, 8, 15 July
1993: 4, 7, 8, 13 July

Differences in the 24-h simulated rainfall between the real and the hypothetical simulations provide model estimates of the impact of surface moisture on regional precipitation for the investigated days. The effects of the contrasted surface moisture availability conditions being prescribed for the whole domain were compared with the effects of having the prescribed contrasted conditions only over the drought- or flood-stricken regions. This might suggest the relative importance of local water recycling and the larger-scale dynamics to rainfall during these events.

3. Results

The 24-h simulated rainfall fields for the unmodified simulations agreed reasonably well with observed fields. However, as seen in previous studies (e.g., Nicolini et al. 1993), locally observed convective rainfall is often underpredicted by mesoscale models. This can be attributed to local storms that are unresolved by the model grid and to the physical parameterizations of the model. Additional predicted fields, such as surface pressure, also showed agreement with the observed fields.

a. July 1988—Drought conditions

Figure 1a shows the inferred initial surface-moisture availability, in the central portion of the domain, for simulations with unmodified surface moisture conditions. In July 1988, drought conditions were most pronounced in the northern and western portion of the simulated domain; this area defines our drought-stricken region. In this section, we present results from a particular simulation thought to be representative of 1988 summer rainfall episodes, namely the 15 July case. Then the results of compositing the three 1988 simulations are presented.

The synoptic situation on 15 July had a weak surface low pressure center moving southeast through eastern North Dakota, with a trailing cold front extending through central South Dakota into western Nebraska. A broad region of high pressure extended from the Gulf coast to Hudson Bay. For this case the pressure gradients were quite weak ahead of the cold front and to the west of the high pressure, resulting in weak southerly flow.

Figure 2 shows the 24-h rainfall patterns for the 15 July set of simulations where the different surface-moisture prescriptions were used. In the observed (unmodified) case (Fig. 2a), the model produced a southwest–northeast strip of rainfall with a peak of 5 mm over northeast Kansas, a rainfall distribution generally similar to observed. Peak values doubled in response to an increase in surface moisture availability in the whole domain to $m = 0.99$ (Fig. 2b). The area affected by rainfall also expanded noticeably. A change of m to 0.99 only in the drought-stricken region, indicated by the framed region in Fig. 1a, produced negligible change in the 24-h rainfall (Fig. 2c).

Figure 3 provides a composite of the three simulated days in July 1988 outlined in Table 1. The total accumulated rainfall has a peak of 11 mm in New Mexico and southeast Nebraska. Only sparse amounts fell in the drought-stricken region (Fig. 3a). Saturating the surface ($m = 0.99$) for the entire domain (Fig. 3b) essentially doubles the rainfall over that simulated for the dry surface conditions. Some expansion of the areal coverage of the rainfall into drought-affected areas was simulated. Saturating only the drought-stricken region produced a weak isolated increase of the precipitation in this region (Fig. 3c).

From these simulations of July 1988, we conclude that the presence of transient saturated surfaces over the drought-stricken region would not have altered the dynamical processes sufficiently to create significant rain in the drought-stricken region. In other regions dynamical effects appeared to also be dominating convective activity, with an almost unnoticeable effect on rainfall as a result of the surface moistening. Transient saturation of the surface of the whole simulation domain would have approximately doubled the overall rainfall in the drought-stricken region, although no new major areas of rain would have developed. This indicates the importance of moisture advection into the drought-stricken area.

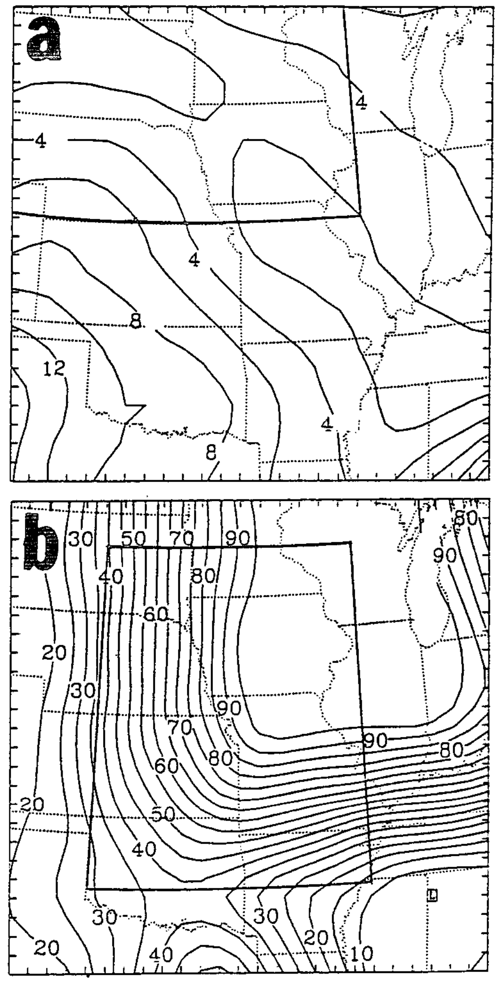

FIG. 1. The inferred surface moisture availability field m for (a) July 1988 and (b) July 1993. Solid frames indicate subdomains with modified m as described in the text. For dry surfaces $m = 0.01$, for saturated surfaces $m = 0.99$.

b. July 1993—Flood conditions

Figure 1b provides the inferred surface moisture availability field for the real-case simulations in July 1993. Flood conditions and related saturated surface conditions were typical in the midwestern states for this period. In the eastern portion of the domain, drought

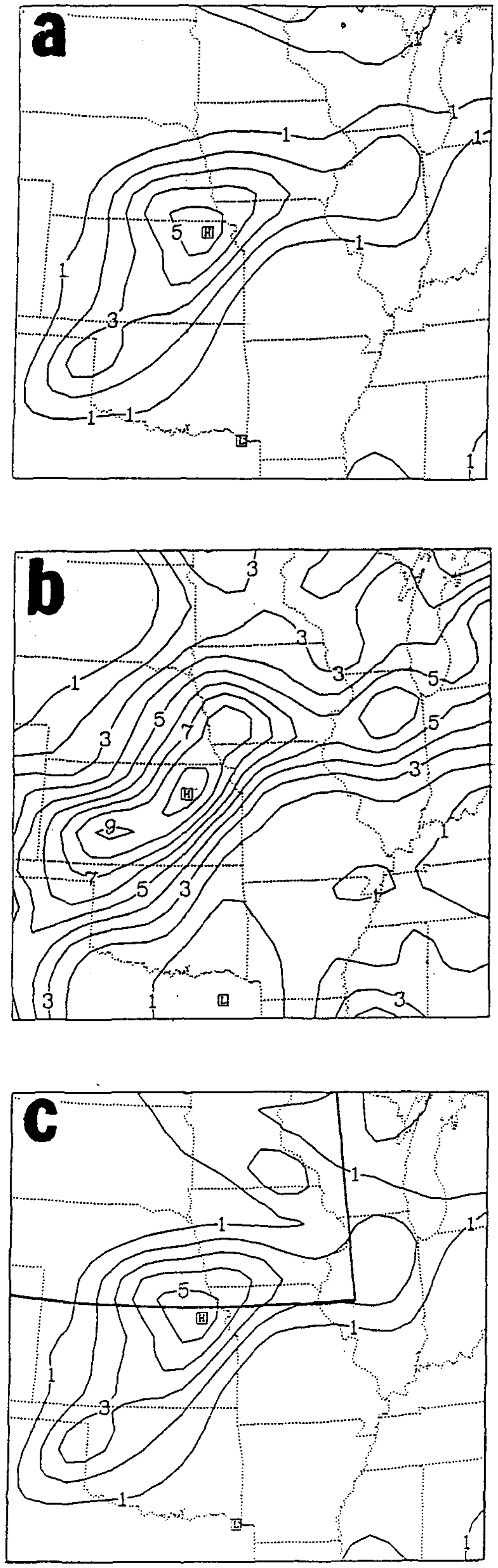

FIG. 2. Simulated 24-h rainfall (mm) valid at 1200 UTC 16 July 1988 with different specifications of m: (a) $m = m_{ob}$, (b) $m = m_s$ for the entire simulation domain, and (c) $m = m_{ob}$, except in the subdomain indicated by the solid frame in Fig. 1a where $m = m_s$.

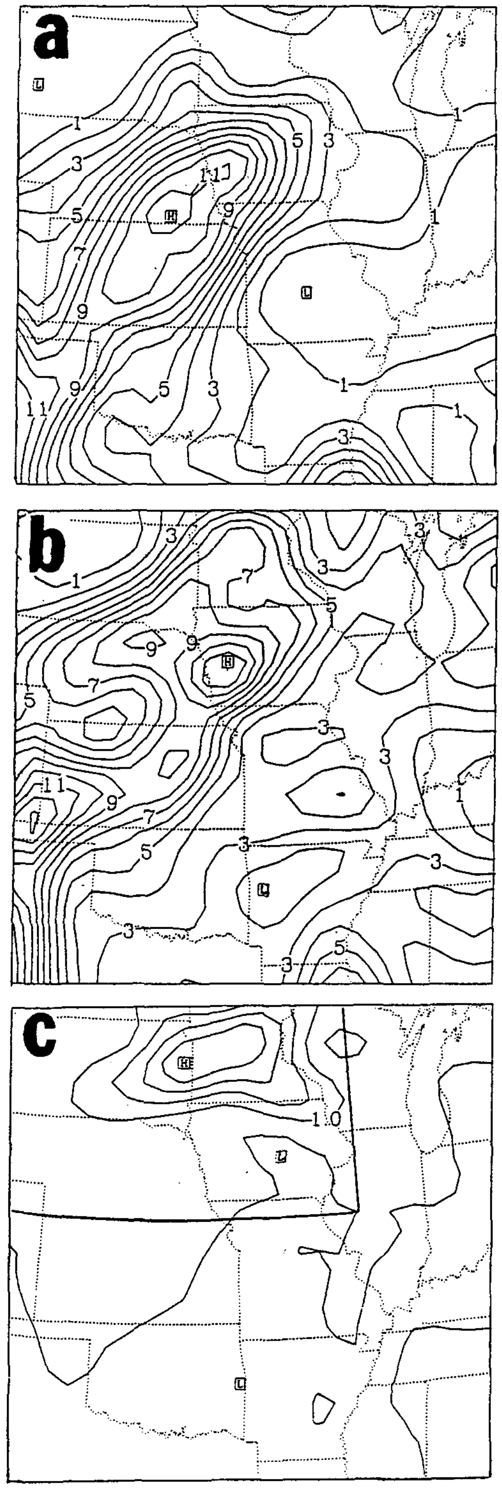

FIG. 3. Rainfall (mm) composites for the three July 1988 days indicated in Table 1. (a) Total rainfall for $m = m_{ob}$; (b) the difference in rainfall between the saturated surface case and the case with observed surface moisture, that is, $(m_s - m_{ob})$; (c) the difference in rainfall between the case with a wet surface only in the subdomain as indicated by the solid frame in Fig. 1a, where $m = m_s$, and the case with observed surface moisture, that is, $(m_{s\,|\,\text{drought-stricken region}} - m_{ob})$.

conditions caused low values of surface moisture availability. As in the previous section, results from a particular simulation, 8 July, will be presented, followed by the composited results.

The synoptic situation for the period beginning at 1200 UTC 8 July consisted of a strong high pressure system anchored over the southeast United States coupled with a persistent trough in the western United States. This pattern had led to a period of sustained moist southerly flow over the central United States, a situation conducive to southerly nocturnal-jet development. A southwest–northeast stationary front passed through Iowa extending from western Kansas into central Michigan. Augustine and Caracena (1994) highlight this pattern as being highly favorable for large MCS (MCC) development. The synoptic situation, in combination with outflow boundaries over Iowa from the previous nights' convective activity, created a situation extremely favorable for heavy rainfall (200 mm fell over parts of the Des Moines River basin in west-central Iowa that evening).

Figure 4 provides an illustration of the simulated 24-h rainfall for the 8 July simulations. The simulated rainfall distribution was similar to that which was observed, except that the simulated local peak of 20 mm in northeast Iowa (Fig. 4a) was too far east and (substantially) smaller than the observed local peak. The eastward displacement of the rainfall peak amounted to an error of about five model grid points. When the surface moisture availability was set to 0.01 over the entire domain (Fig. 4b), some shrinkage of the area affected by rainfall occurred, with a drop of peak rainfall to 14 mm. Prescribing a dry surface over the flood-stricken region, indicated by the framed region in Fig. 1b, caused a small reduction of the peak rainfall and a slight shrinkage of the areal coverage of the rainfall (Fig. 4c) compared with the case presented in Fig. 4b.

Figure 5a shows the composited rainfall from the simulations of the four July 1993 days as outlined in Table 1. Note, that for these simulations the observed surface moisture availability was used. The composite represents only a fraction (about 10%) of the observed July total rainfall, although its spatial distribution resembles the observed monthly pattern (based on data from H. Hillaker 1994, personal communication). The peak rainfall simulated was 48 mm located over eastern Iowa, with a secondary peak of 24 mm over central Kansas (Fig. 5a). At the location of these peaks in the composite rainfall, a drop of 30%–40% in the rainfall was simulated when the surface moisture availability was prescribed a value of 0.01 over the whole domain (Fig. 5b). In general, the reduction tends to be relatively more pronounced in the southern part of the domain than in the northern part. It is suggested, therefore, that for the situations included in the composite, dynamical processes dominated the surface moisture–related contribution to deep convection in the northern part of the domain. Reduction of the areal coverage of

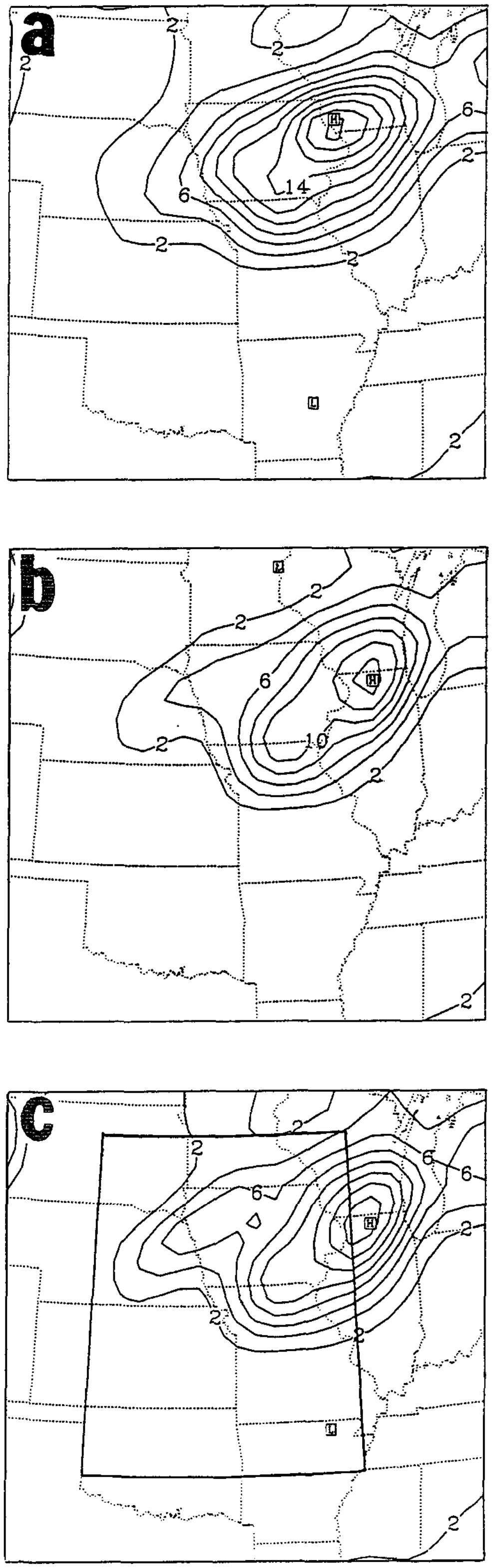

FIG. 4. Simulated 24-h rainfall (mm) valid at 1200 UTC 9 July 1993 with different specifications for m: (a) $m = m_{ob}$, (b) $m = m_d$ for the entire simulation domain, and (c) $m = m_{ob}$, except in the subdomain indicated by the solid frame in Fig. 1b where $m = m_d$.

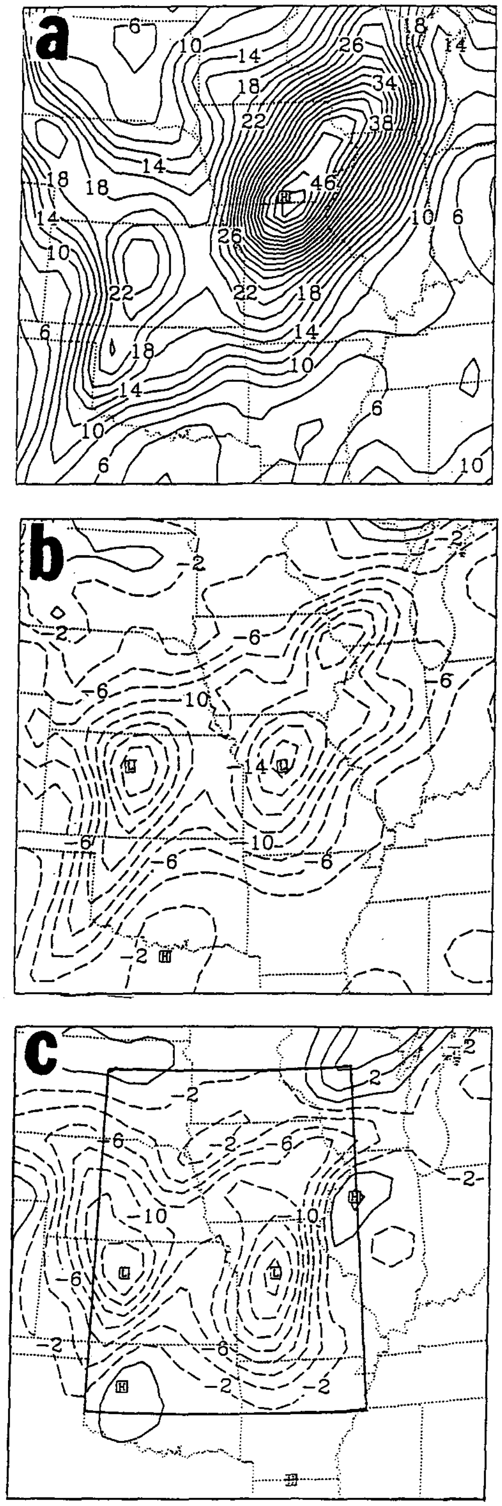

FIG. 5. Rainfall (mm) composites for the four July 1993 days indicated in Table 1. (a) Total rainfall for $m = m_{ob}$; (b) the difference in rainfall between the dry surface case and the case with observed surface moisture, that is, $(m_d - m_{ob})$; (c) the difference in rainfall between the case with a dry surface only in the subdomain as indicated by the solid frame in Fig. 1b, where $m = m_d$, and the case with observed surface moisture, $(m_{d|\text{flood-stricken region}} - m_{ob})$.

the dry surface from the entire domain to the flood-stricken subdomain (Fig. 5c) caused very similar changes to that when the entire domain was dry (Fig. 5b). This suggests that the reduction in rainfall due to the transient drying of the entire domain was due mainly to the drying out of the flood-stricken area. This suggests that local water recycling played a relatively more important role in the floods of 1993 than the drought of 1988.

4. Conclusions

Sensitivity simulations were carried out for the *preliminary* evaluation of the role of hypothetical transient changes in surface moisture, and thus evapotranspiration, on rainfall patterns for the Midwest during periods of drought and flood. The illustrative evaluations in this note were made by establishing a 24-h contrasted surface moisture availability to force the hypothetical simulations. Results of the simulations suggest that a transient saturation of the drought-stricken area would have had little impact on the absolute rainfall that occurred in the drought-year simulations. That is, the larger-scale circulation was most likely responsible for the deficient rainfall over this region on these days. Larger *relative* changes in rainfall were simulated for these cases when the entire domain was saturated, but the general rainfall pattern was similar, indicating that no new areas of rainfall developed. In contrast, for flood conditions the simulations suggested that the saturated surface, over the flood-stricken region, was quite significant in contributing to the total rainfall, although relative changes were lower than those for drought conditions. The results suggest that during drought conditions, the relative contribution to water recycling by local evapotranspiration is not as important as during flood conditions. However, if a much larger area than the drought- or flood-stricken regions were to experience transient contrasting surface-moisture conditions, the contribution of water recycling to rainfall during drought might become as high as 100%, but it would remain at about 30%–40% for the flood conditions.

It should be noted that the simulated local rainfall peaks were noticeably less than observed. This may be due in part to coarse model resolution, inadequacies in initial conditions, and use of a relatively simple cumulus convection scheme. These deficiencies should be addressed in the future.

GCM simulations of extended summer drought conditions (e.g., Atlas et al. 1993) have suggested that suppression of evapotranspiration and increased sensible heat flux have an accumulated seasonal negative feedback on the large-scale dynamics. The impacts of such feedbacks, should they have occurred during the drought of 1988 and the flood of 1993 (i.e., the events studied in this paper), are included in these simulations, since the data used to initialize the model would reflect these trends in the large-scale dynamics.

On an historical note, the question as to the contribution of the dry surface conditions during the Dust Bowl of the mid-1930s to the severity of that drought has been intriguing to many researchers over the years. Even now, with very refined models, it would be a difficult question to address due to the sparsity of upper-air data in that period. To the extent that circulation features present during 1988 are typical of large-scale droughts, it can be suggested that occasional highly wet surface conditions within the drought-stricken area would have had little direct effect on the absolute amount of rainfall that resulted from the isolated rain events in that period and that a transient wetting of the surface would likely not have created new regions of precipitation.

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